Power Quality Issues and its Mitigation Techniques

A Thesis Submitted in Partial Fulfilment
Of the Requirements for the Award of the Degree of

MASTER OF TECHNOLOGY

in

Electrical Engineering

by

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Department of Electrical Engineering
National Institute of Technology Rourkela
2012-2014

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Under the Supervision of

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National Institute of Technology Rourkela

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Dedicated

To

My beloved Parents

DEPARTMENT OF ELECTRICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

ORISSA, INDIA-769008

CERTIFICATE

This is to certify that the thesis entitled **"Power Quality Issues and its Mitigation Techniques"**, submitted by **Mr. SANDEEP KUMAR N** in partial fulfillment of the requirements for the award of **Master of Technology in Electrical Engineering** with specialization in "**Power Electronics and Drives**" at National Institute of Technology, Rourkela. A Bona fide record of research work carried out by him under my supervision and guidance. The candidate has fulfilled all the prescribed requirements. The Thesis which is based on candidates own work, has not submitted elsewhere for a degree/diploma.

In my opinion, the thesis is of standard required for the award of a master of technology degree in Electrical Engineering.

Place: Rourkela

Date:

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ABSTRACT

The electrical energy is one of the easily used forms of energy. It can be easily converted to other forms of energy. With the advancement of technology, the dependency on the electrical energy has been increased greatly. Computer and telecommunication networks, railway network banking, post office, life support system are few application that just cannot function without electricity. At the same time these applications demand qualitative energy.

However, the quality of power supplied is affected by various internal and external factors of the power system. The presence of harmonics, voltage and frequency variations deteriorate the performance of the system. In this project the frequently occurring power quality problem- voltage variation is discussed.

The voltage sag/dip is the most frequently occurring problem. There are many methods to overcome this problem. Among them the use of FACT devices is an efficient one. This project presents an overview of the FACT devices like- DVR, D-STATCOM, and Auto-Transformer in mitigating voltage sag.

Each one of the above device is studied and analyzed. And also the control strategies to control these devices are presented in this project. The proposed control strategies are simulated in MATLAB SIMULINK environment and the results are presented. A comparative study based on the performance of these devices in mitigating voltage sag is also presented.

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS USED

FACTS	Flexible AC Transmission System
DVR	Dynamic Voltage Restorer
PI	Proportional Integral
THD	Total Harmonic Distortion
IEEE	Institute of Electrical and Electronics Engineers
PWM	Pulse Width Modulation
KW	Kilo Watt
Hz	Hertz
F	Farad
PCC	Point of Common Coupling
VSI	Voltage Source Inverter

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 Introduction

1.2 Literature Review

1.3 Research Motivation

1.4 Thesis Objectives

1.5 Organization of Thesis

1.1INTRODUCTION

Electrical energy is the most efficient and popular form of energy and the modern society is heavily dependent on the electric supply. The life cannot be imagined without the supply of electricity. At the same time the quality and continuity of the electric power supplied is also very important for the efficient functioning of the end user equipment. Most of the commercial and industrial loads demand high quality uninterrupted power. Thus maintaining the qualitative power is of utmost important.

The quality of the power is affected if there is any deviation in the voltage and frequency values at which the power is being supplied. This affects the performance and life time of the end user equipment. Whereas, the continuity of the power supplied is affected by the faults which occur in the power system. So to maintain the continuity of the power being supplied, the faults should be cleared at a faster rate and for this the power system switchgear should be designed to operate without any time lag.

The power quality is affected many problems which occur in transmission system and distribution system. Some of them are like- harmonics, transients, sudden switching operations, voltage fluctuations, frequency variations etc. These problems are also responsible in deteriorating the consumer appliances. In order to enhance the behavior of the power system, these all problems should be eliminated.

With the recent advancements in power electronic devices, there are many possibilities to reduce these problems in the power system. One of them is the use of Flexible AC Transmission System (FACTS) devices. The connection of these devices in the power system helps in improving the power quality and reliability. In this project the mitigation of voltage sag using FACTS devices is studied and analyzed.

1.2 LITERATURE REVIEW

The quality of power delivered to the end user is very important as the performance of the consumer’s equipment is heavily dependent on it. But the power quality is affected by various factors like voltage and frequency variations, presence of harmonics, faults in the power network etc. Among them the voltage variations (sag) is one of the most frequently occurring problem.

There are many methods to mitigate the voltage sag and among them the best way is to connect a FACT device at the point of interest. The well-known devices like D-STATCOM, DVR, and UPQC are used for this purpose. The world's earliest DVR 's installation was done at Duke Power Company's 12.47kV substation in Anderson, South Carolina in 1996. After that immediately then ABB, Siemens and other companies have also focused and worked hard for several years to achieve the design patterns and finally developed their own patterns of the products to ensure the quality of voltage-sensitive load. Therefore, there is lot of research in this field.

A survey on the structure and control strategies of the DVR is presented in [2]. It discusses how a DVR can be controlled to mitigate voltage sag. It also presents the other advantages of connecting a DVR to the power network. The design of a DVR for voltage sag mitigation application is presented in [1]. It also presents the response of the DVR when sag is created.

The other FACT device that is used for voltage sag application is D-STATCOM. The basic structure of D-STATCOM is explained in [3]. This paper discusses the working principle of the device. The different modes of operation of a D-STATCOM are clearly presented in [4]. The control strategy to control the device is discussed in [5]. It also presents the MATLAB based modeling of the system.

A comparison between the DVR and D-STATCOM in mitigating voltage sag is given in [6]. It states that the power injection required by D-STATCOM to mitigate a given voltage sag is more compared to that of DVR. But the D-STATCOM is capable of mitigating higher voltage sags without injecting active power. However, both these devices include switching losses.

To overcome the drawback of these devices, a new technique to mitigate voltage sag is proposed in [7]. It presents a PWM switched auto transformer to mitigate the voltage sag. As this topology uses only one power electronic switch, the switching losses are reduced greatly and the efficiency of the system is increased. This paper presents control strategy to control the IGBT switch such that the auto transformer is responded intact with the voltage imbalance. The proposed control strategy is validated with simulation results.

1.3 RESEARCH MOTIVATION

The operation of most of the loads depend greatly on the voltage level at which the power is being supplied to them. But in the power system there may be deviations in the voltage and frequency levels due to sudden switching operations, faults etc. In order to maintain the voltage at the Point of Common Coupling (PCC) at a standard level there is a need to connect some device at the PCC. The FACT device suits best for this purpose. In this project a study on different FACT devices for the mitigation of voltage unbalance is carried out.

1.4 THESIS OBJECTIVES

The objectives of this project are:

- To investigate the techniques to mitigate voltage sag, swell
- To study and analyze the behavior of FACT devices in reducing the voltage unbalance
- To select a device that best suits the application
- To control the device such that desired performance is obtained

1.5 ORGANIZATION OF THESIS

The whole thesis is divided into five chapters including introduction and each chapter is organized in the following way-

Chapter 2 deals with the Power Quality Problems and their effect on the consumer appliances. It focuses on the causes of major power quality problems like voltage sag and swell. It also presents mitigation techniques to overcome these problems.

Chapter 3 deals with the FACT devices that are helpful in mitigating the voltage sag. It presents the basic working principle of these devices along with the control strategy. It also presents a comparison between the different devices available for this purpose.

Chapter 4 presents the MATLAB simulation results of the proposed devices. This chapter discusses how the selected device works practically in mitigating the voltage unbalance.

Chapter 5 presents the conclusions of the work done along with the future scope followed by references.

CHAPTER 2

POWER QUALITY PROBLEMS

2.1 Introduction

The electric power network has undergone several modifications from the time of its invention. The modern electric power network has many challenges that should be met in order to deliver qualitative power in a reliable manner. There are many factors both internal and external that affect the quality and quantity of power that is being delivered. This chapter discusses the different power quality problems, their causes and consequences.

2.2 Power Quality

The quality of electric power delivered is characterized by two factors namely- “continuity” of supply and the “quality” of voltage. As indicated by IEEE standard 1100, Power Quality is characterized as-

"The idea of controlling and establishing the touchy supplies in a manner that is suitable for the operation of the gear."

2.3 Power quality Problems

There are many reasons by which the power quality is affected. The occurrence of such problems in the power system network is almost indispensable. Therefore, to maintain the quality of power care must be taken that suitable devices are kept in operation to prevent the consequences of these problems. Here an overview of different power quality problems with their causes and consequences is presented.

2.3.1 Interruptions:

It is the failure in the continuity of supply for a period of time. Here the supply signal (voltage or current) may be close to zero. This is defined by *IEC* (International Electro technical Committee) as “lower than 1% of the declared value” and by the *IEEE* (IEEE Std. 1159:1995) as “lower than 10%”. Based on the time period of the interruption, these are classified into two types [8]-

A. *Short Interruption:*

If the duration for which the interruption occurs is of few mille seconds then it is called as short interruption.

Causes:

The causes of these interruptions are-

- Opening of an Automatic Re-closure
- Lightening stroke or Insulation Flash over

Consequences:

- The data storage system gets affected
- There may be malfunction of sensitive devices like- PLC's, ASD's

B. *Long Interruptions:*

If the duration for which the interruption occur is large ranging from few mille seconds to several seconds then it is noticed as long interruption. The voltage signal during this type of interruption is shown in Fig. 2.1.

Causes:

The causes of these interruptions are-

- Faults in power system network
- Human error
- Improper functioning of protective equipment

Consequences:

This type of interruption leads to the stoppage of power completely for a period of time until the fault is cleared.

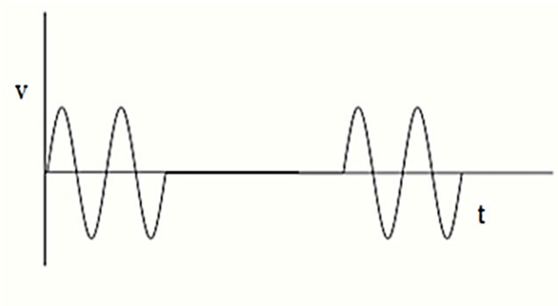


Fig.2.1 Voltage Signal with Long Interruption

2.3.2 Waveform Distortion:

The power system network tries to generate and transmit sinusoidal voltage and current signals. But the sinusoidal nature is not maintained and distortions occur in the signal. The cause of waveform distortions are [8]-

- **DC Offset:** The DC voltage which is present in the signal is known as DC offset. Due to the presence of DC offset, the signal shifts by certain level from its actual reference level.
- **Harmonics:** These are voltage and current signals at frequencies which are integral multiples of the fundamental frequency. These are caused due to the presence of non-linear loads in the power system network.
- **Inter Harmonics:** These are the harmonics at frequencies which are not the integral multiples of fundamental frequency.
- **Notching:** This is a periodic disturbance caused by the transfer of current from one phase to another during the commutation of a power electronic device.
- **Noise:** This is caused by the presence of unwanted signals. Noise is caused due to interference with communication networks.

2.3.3 Frequency Variations:

The electric power network is designed to operate at a specified value (50 Hz) of frequency. The frequency of the framework is identified with the rotational rate of the generators in the system. The frequency variations are caused if there is any imbalance in the supply and demand. Large variations in the frequency are caused due to the failure of a generator or sudden switching of loads.

2.3.4 Transients:

The transients are the momentary changes in voltage and current signals in the power system over a short period of time. These transients are categorized into two types- impulsive, oscillatory. The impulsive transients are unidirectional whereas the oscillatory transients have swings with rapid change of polarity.

Causes:

There are many causes due to which transients are produced in the power system. They are-

- Arcing between the contacts of the switches
- Sudden switching of loads
- Poor or loose connections
- Lightening strokes

Consequences:

- Electronics devices are affected and show wrong results
- Motors run with higher temperature
- Failure of ballasts in the fluorescent lights
- Reduce the efficiency and lifetime of equipment

2.3.5 Voltage Sag:

The voltage sag is defined as the dip in the voltage level by 10% to 90% for a period of half cycle or more. The voltage signal with sag in shown in Fig. 2.2.

Causes:

The causes of voltage sag are-

- Starting of an electric motor, which draws more current
- Faults in the power system
- Sudden increase in the load connected to the system

Consequences:

- Failure of contactors and switchgear
- Malfunction of Adjustable Speed Drives (ASD’s)

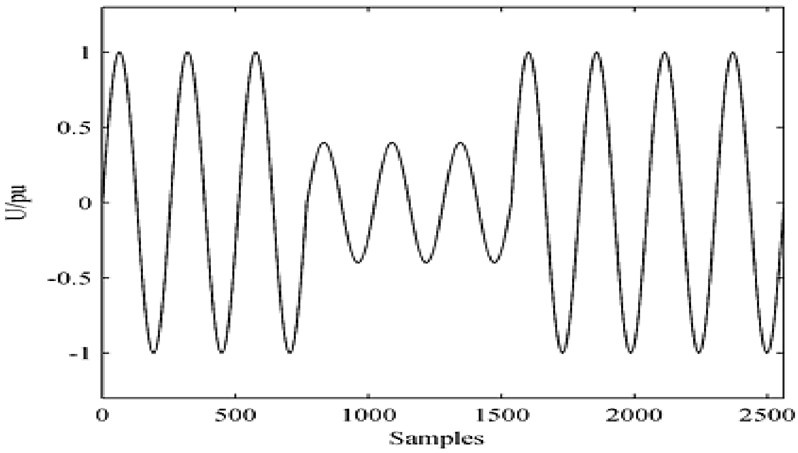


Fig.2.2 Voltage Sag

2.3.6 Voltage Swell:

Voltage swell is defined as the rise in the voltage beyond the normal value by 10% to 80% for a period of half cycle or more. The voltage signal with swell in shown in Fig.2.3.

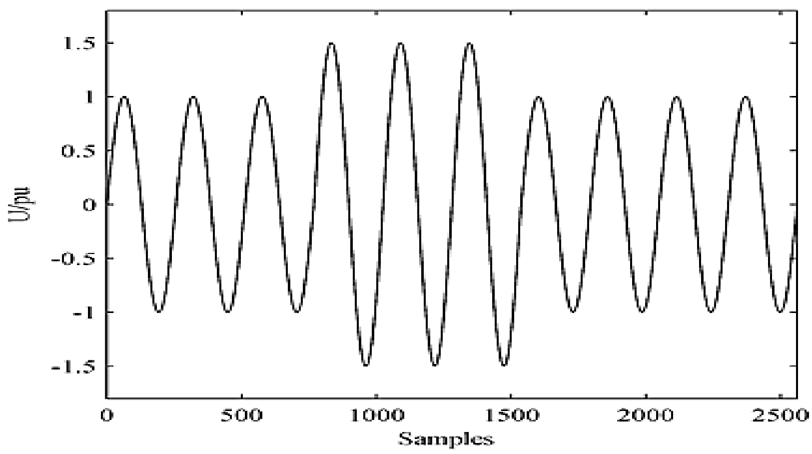


Fig.2.3 Voltage Swell

Causes:

- De-energization of large load
- Energization of a capacitor bank
- Abrupt interruption of current
- Change in ground reference on ungrounded phases

Consequences:

- Electronic parts get damaged due to over voltage
- Insulation breakdown
- Overheating

2.3.7 Voltage Unbalance:

The unbalance in the voltage is defined as the situation where the magnitudes and phase angles between the voltage signals of different phases are not equal.

Causes:

- Presence of large single-phase loads
- Faults arising in the system

Consequences:

- Presence of harmonics
- Reduced efficiency of the system
- Increased power losses
- Reduce the life time of the equipment

2.3.8 Voltage Fluctuation:

These are a series of a random voltage changes that exist within the specified voltage ranges. Fig. 2.4 shows the voltage fluctuations that occur in a power system.

Causes:

These are caused by the

- Frequency start/ stop of electric ballasts
- Oscillating loads
- Electric arc furnaces

Consequences:

- Flickering of lights
- Unsteadiness in the visuals

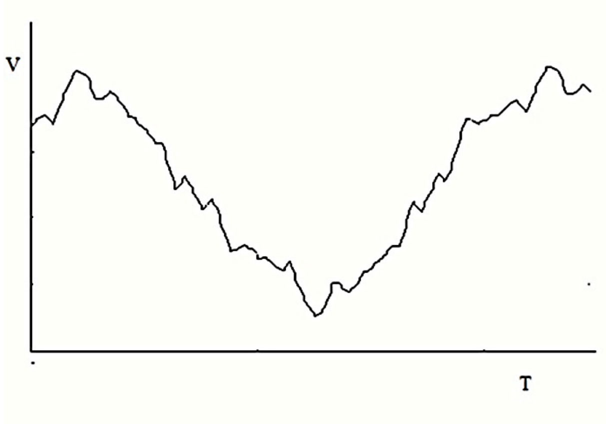


Fig.2.4 Voltage Fluctuation

Among the different power quality problems discussed, the under voltage or voltage sag is the prominent one as it occurs often and affects the power system network largely. Therefore, in this project main focus is given on voltage sag and its mitigation techniques.

2.4 VOLTAGE SAG ANALYSIS

2.4.1 Definition:

According to standard IEEE 1346-1998, Voltage Sag is defined as-

"A decrease in rms voltage or current at the power frequency for durations of 0.5 cycle to 1 min.

Typical values are 0.1 to 0.9 pu."

2.4.2 Characteristics of Voltage Sag:

The voltage sag is characterized by its magnitude, duration and phase angle jump. Each of them is explained below in detail.

A. Magnitude of Sag:

A sag magnitude is defined as the minimum voltage remaining during the event. The magnitude can be defined in a number of ways. The most common approach is to use the rms voltage. The other alternatives are to use fundamental rms voltage or peak voltage. Thus, sag is considered as the residual or remaining voltage during the event. In case of three-phase system where the dip in voltage is not same in all phases, the phase with lowest dip is used to characterize sag.

The magnitude of voltage sag at a certain point depend on-

- Type of fault
- Fault impedance
- System Configuration
- Distance of the fault from the point of consideration

B. Duration of Sag:

Table-I Classification of Sag

Type of Sag	Duration	Magnitude
Instantaneous	0.5 - 30 cycles	0.1 - 0.9 pu
Momentary	30 cycles - 3 s	0.1 - 0.9 pu
Temporary	3 s – 1 min	0.1 - 0.9 pu

The duration of sag is the time for which the voltage is below a threshold value. It is determined by the fault clearing time. In a three phase system all the three rms voltages should be considered to calculate the duration of the sag. A sag starts when one of the phase rms voltage is less than the threshold and continues until all the three phase voltages are recovered above the threshold value. Based on the duration of sag, the voltage sags are classified as shown in Table-I.

C. Phase-Angle Jump:

The short circuits in power system not only cause a dip in voltage, but also change the phase angle of the system. The change of phase angle is called as "Phase-Angle Jump". It causes the shift in zero crossing of the instantaneous voltage. This phenomenon affects the power electronic converters which use phase angle information for their firing.

D. Point-on-Wave:

To perfectly characterize sag, the point-on-wave where the sag starts and where it ends should be found with high precession. The point-on-wave is nothing but the phase angle at which the sag occurs. These values are generally expressed in radians or degrees.

2.4.3 Voltage Sag Mitigation Analysis:

To prevent the occurrence of voltage sag preventive measures can be taken at different stages. They are-

A. During the Production of Equipment:

The basic and economical solution is to strengthen the sensitive devices to the power quality problems. This prevents the damage of these devices to the abnormalities in the power system. The device manufacturers use a specific curve like ITIC (Information Technology Industry Council) curve during manufacturing. This curve specifies the withstanding capability of sensitive devices like computers, PLC’s, ASD’s during voltage imbalance occurring in the system. Based on this curve the design is improved so that the damage of these devices is prevented.

B. Analysis of the Causes:

The second basic way to prevent the occurrence of voltage sag is to analyze the causes that lead to voltage imbalance. Improving the poor wiring and weak grounding systems can prevent the damage of the sensitive equipment. The medium which causes power quality problems should be avoided to the extent possible.

C. Power Conditioning Equipment:

The use of power conditioning equipment is the most common solution to protect the power system network from these problems. Most of the power conditioning equipment is voltage monitoring devices as most of the faults that occur in power system are voltage imbalance faults. These devices may be connected at the source side or in the transmission network, or at the load end. In general, these devices are connected at the point of common coupling (PCC) where the load is connected to the supply. This is done as the cost of the power conditioning device increases from load end to source side. There are different power conditioning devices like-

i. ***Line-voltage regulators***: These are special transformers connected in series with the transmission line designed to regulate the voltage in accordance with the changes in the system. Examples of line voltage regulators are- tap changing transformers, CVT's, buck-boost regulators etc.
ii. ***M-G Sets (Motor-generator Sets)***: These M-G sets are installed at the load side in order to supply power to critical loads during the interruptions from the power supply company. In this maintenance and safety are main concern.
iii. ***Magnetic Synthesizers:*** These employ resonant circuits made of inductors and capacitors. They are used to filter the harmonics from affecting the loads. But these are bulky and noisy.
iv. ***SVC (Static VAR Compensators)***: These also use passive elements like inductors and capacitors. But the use of solid state switches to control the voltage injection increases their efficiency. The switches are controlled such that correct magnitude of voltage is injected at correct point of time so that voltage fluctuations are reduced. But these are expensive.
v. ***UPS (Uninterruptible Power Supplies)***: It provides a constant voltage during both voltage sags and outages from a battery or super conducting material. The main parts of an UPS are battery, rectifier and an inverter.
vi. ***SMES (Superconducting magnetic energy storage)***: SMES stores electrical energy within a superconducting magnet. It provides a large amount of power (750 KVA to 500 MVA) within a short time.
vii. ***Custom Power Devices:*** All the above mentioned conventional devices are not suitable to mitigate voltage disturbances effectively. Therefore, there is a need to use new type of devices known as Custom Power Devices. These are power electronic equipment aimed to help in mitigating power quality problems. These are of many types like- Dynamic Voltage Regulator (DVR), D-STATCOM, auto transformer, UPQC etc. In this project a study of these devices is carried out for improving the power quality.

2.5 SUMMARY:

This chapter presents the various problems that affect the quality of power in a system. It explained the causes and consequences of the problem. A focus is made on Voltage Sag, as it is the most frequently occurring problem. The characteristics and also the mitigation techniques are discussed to give an overview on the voltage sag. Among the various mitigation techniques that are available, the use of custom power devices is the most effective and economical solution.

CHAPTER 3

STUDY OF DVR, D-STATCOM AND AUTO TRANSFORMER FOR VOLTAGE SAG MITIGATION

3.1 INTRODUCTION

The voltage sag is a major problem that the power system network is facing now-a-days. This is a severe problem and affects the functioning of the equipment. Therefore, this problem should be mitigated in order to maintain the efficiency of the power network. The use of custom power devices solves this problem. This chapter presents the basic structure and working principle of different devices like DVR, D-STATCOM, Auto Transformer used to mitigate the voltage sag.

3.2 Dynamic Voltage Restorer (DVR)

A Dynamic Voltage Restorer is a power electronic converter based gadget intended to ensure the discriminating burdens from all supply-side unsettling influences other than deficiencies [1]. It is connected in arrangement with the distribution feeder for the most part at the purpose of regular coupling.

3.2.1 Basic Structure:

The DVR is a series connected power electronic device used to inject voltage of required magnitude and frequency. The basic structure of a DVR is shown in Fig. 3.1. It contains the following components-

- Voltage Source Inverter (VSI)
- DC storage unit
- Filter circuit
- Series Transformer

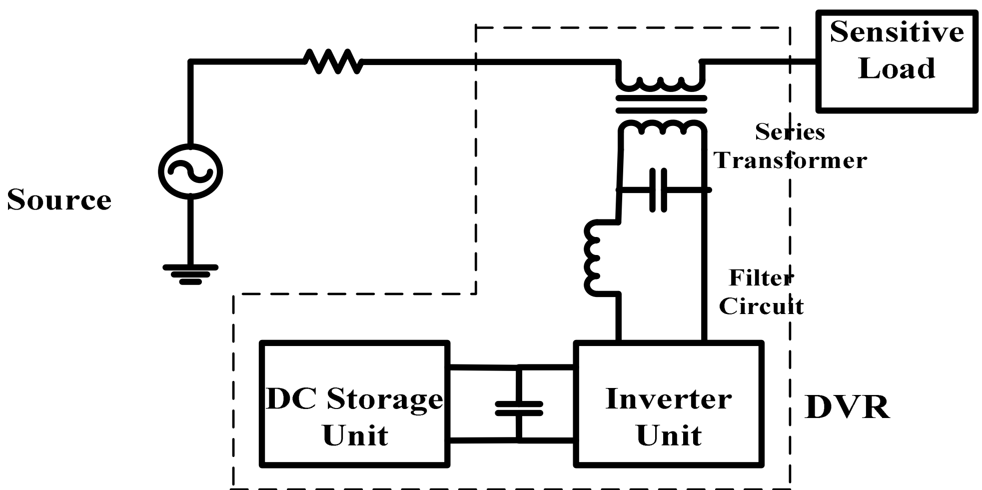


Fig.3.1 Basic Structure of DVR

i. **Voltage Source Inverter (VSI):** The VSI consists of solid state switches like IGBT's or GTO's used to convert the DC input to AC. It is used to inject the AC voltage to compensate the decrease in the supply voltage. The switches of the VSI are operated based on the pulse width modulation (PWM) technique to generate the voltage of required magnitude and frequency.

ii. **DC Storage Unit:** The storage unit may consist of batteries, capacitors, flywheel, or super magnetic energy storage (SMES). For DVR with internal storage capacity, energy is taken from the faulted grid supply during the sag. This configuration is shown in Fig. 3.2. Here a rectifier is used to convert the AC voltage from the grid to DC voltage required by the VSI.

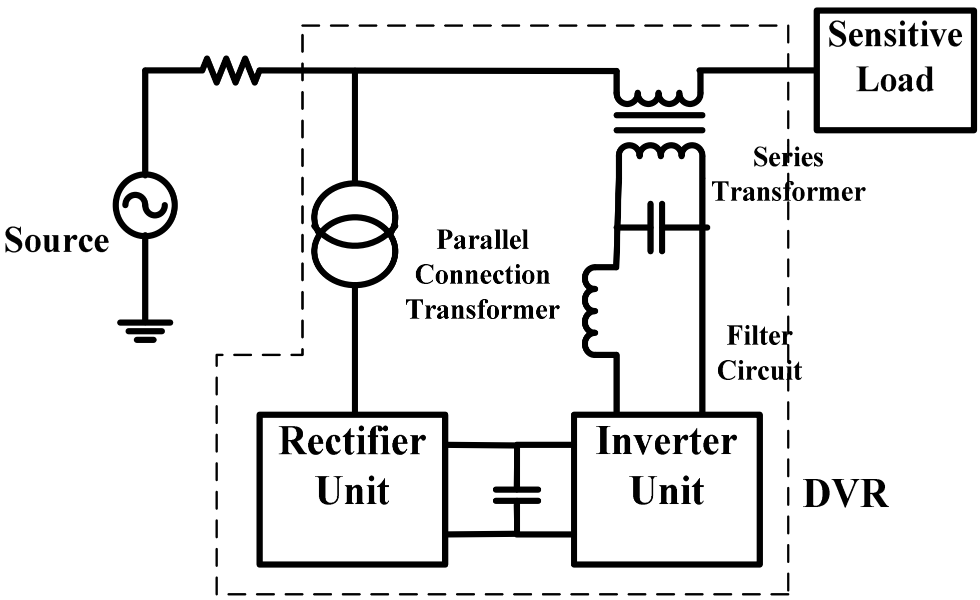


Fig.3.2 DVR without Internal Storage

iii. **Filter Circuit:** An LC filter is connected at the output of the VSI to filter the harmonics that are present in the output voltage of VSI. It also reduces the dv/dt effect on the windings of the transformer [2].

iv. **Series Transformer:** A series transformer is used to connect the DVR with the distribution feeder. In case of three phase system, three single phase transformers are used to connect the DVR with the power network.

3.2.2 Operating Principle:

The main operation of the DVR is to inject voltage of required magnitude and frequency when desired by the power system network. During the normal operation, the DVR will be in stand-by mode. During the disturbances in the system, the nominal or rated voltage is compared with the voltage variation and the DVR injects the difference voltage that is required by the load. The equivalent circuit of a DVR connected to the power network is shown in Fig. 3.3. Here V_s is the supply voltage, V_{inj} is the voltage injected by the DVR and V_L is the load voltage.

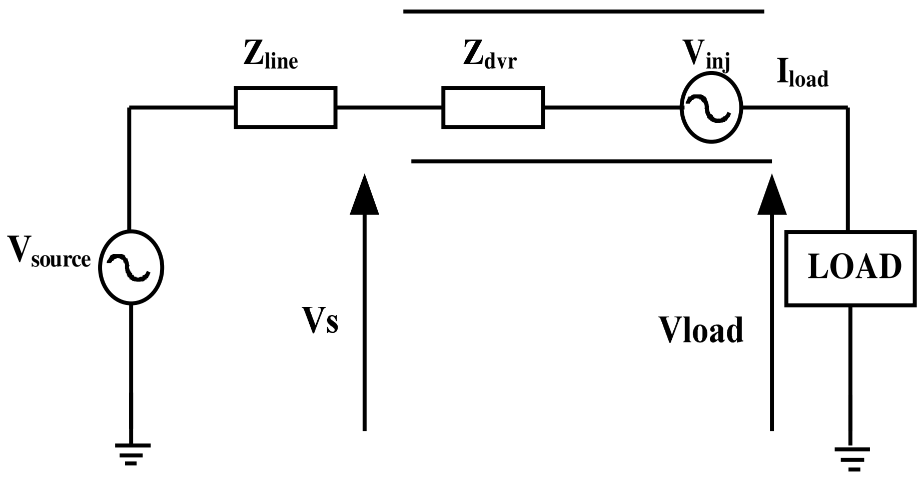


Fig .3.3 Equivalent Circuit Diagram of DVR

3.2.3 Control Strategy:

The principle contemplations for the control of a DVR are- identification of the begin and completion of the hang, voltage reference era, transient and unfaltering state control of the infused voltage and security of the system[2].Any control technique implemented to control the DVR should fulfill all the above aspects.

The basic idea behind the control strategy is to find the amount by which the supply voltage is dropped. For this the three phase supply voltage is compared with the reference voltage V_{ref}. If there is voltage sag (or any other voltage imbalance) then an error occurs. This error voltage is then sent to the PWM generator, which generates the firing pulses to the switches of the VSI such that required voltage is generated. The whole control strategy can be implemented in 2-ϕ rotating (d-q) coordinate system. The flow chart of the control technique based on dq0 transformation is shown in Fig. 3.4.

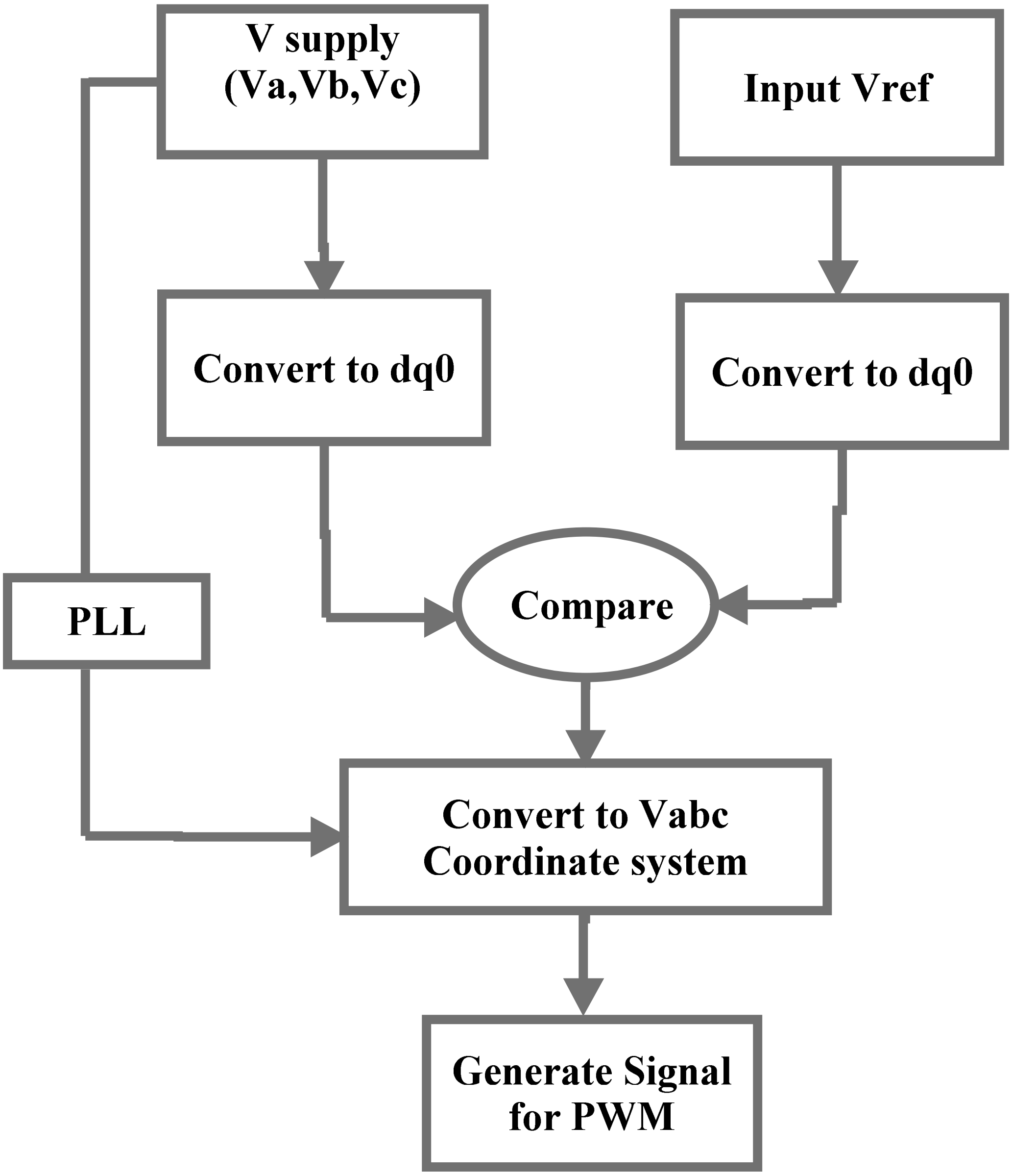


Fig.3.4 Flowchart of Control Algorithm for DVR

3.2.4 Applications of DVR:

There are many applications of DVR in addition to mitigate voltage sag. They are [2]-

- DVR can be used to compensate the load voltage harmonics and improves the power quality of the system.

- DVR can be used under system frequency variations to provide the real power required by the load. This is done by connecting a uncontrolled rectifier at the input of the VSI.
- DVR can also protect the system against voltage swell or any other voltage imbalances that occur in the power system.

3.3 D-STATCOM

A Distribution Static Compensator is in short known as D-STATCOM. It is a power electronic converter based device used to protect the distribution bus from voltage unbalances. It is connected in shunt to the distribution bus generally at the PCC.

3.3.1 Basic Structure:

D-STATCOM is a shunt connected device designed to regulate the voltage either by generating or absorbing the reactive power. The schematic diagram of a D-STATCOM is as shown in Fig. 3.5. It contains-

- DC Capacitor
- Voltage Source Inverter (VSI)
- Coupling Transformer
- Reactor

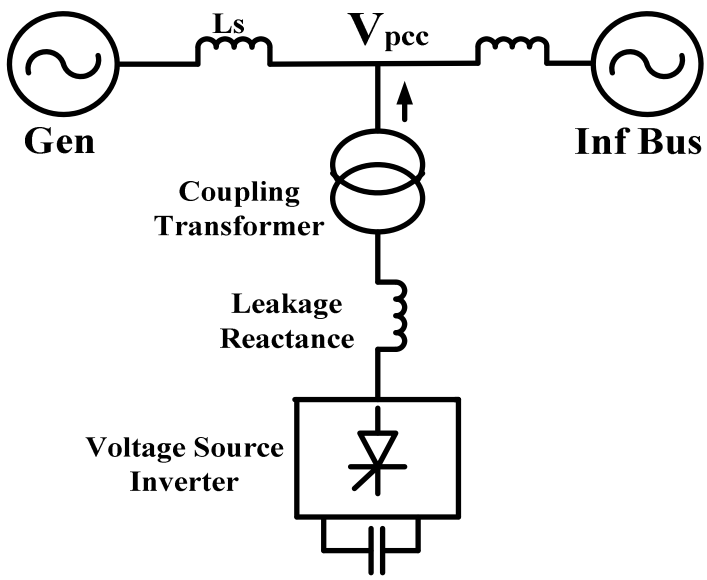


Fig.3.5 Schematic Diagram of D-STATCOM

As in the case of DVR, the VSI generates voltage by taking the input from the charged capacitor. It uses PWM switching technique for this purpose. This voltage is delivered to the system through the reactance of the coupling transformer. The voltage difference across the reactor is used to produce the active and reactive power exchange between the STATCOM and the transmission network [3]. This exchange is done much more rapidly than a synchronous condenser and improves the performance of the system.

3.3.2 Operating Principle:

A D-STATCOM is capable of compensating either bus voltage or line current. It can operate in two modes based on the parameter which it regulates [4]. They are-

- **Voltage Mode Operation:** In this mode, it can make the bus voltage to which it is connected a sinusoid. This can be achieved irrespective of the unbalance or distortion in the supply voltage.
- **Current Mode Operation:** In this mode of operation, the D-STATCOM forces the source current to be a balanced sinusoid irrespective of the load current harmonics.

The basic operating principle of a D-STATCOM in voltage sag mitigation is to regulate the bus voltage by generating or absorbing the reactive power. Therefore, the D-STATCOM operates either as an inductor or as a capacitor based on the magnitude of the bus voltage.

- Inductive Operation: If the bus voltage magnitude (V_B) is more than the rated voltage then the D-STATCOM acts as an inductor absorbing the reactive power from the system. The circuit and phasor diagram are shown in Fig. 3.6.

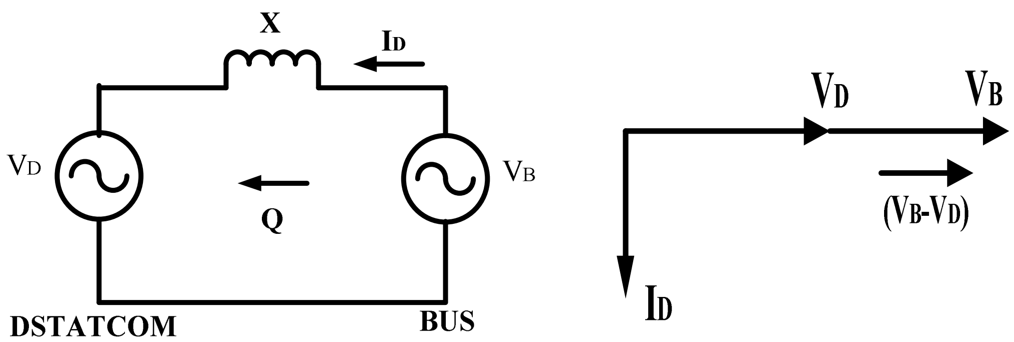


Fig.3.6 Inductive Mode of Operation

- Capacitive Operation: If the bus voltage magnitude (V_B) is less than the rated voltage then the D-STATCOM acts as a capacitor generating the reactive power to the system. The circuit and phasor diagram of this mode of operation are shown in Fig. 3.7.

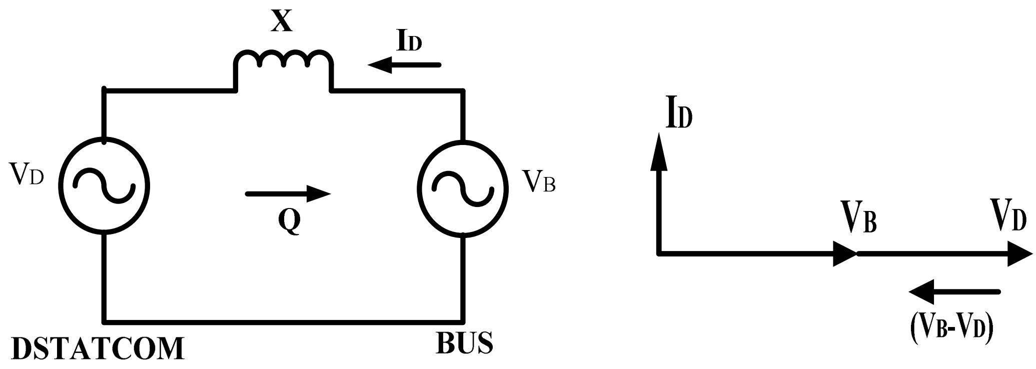


Fig.3.7 Capacitive Mode of Operation

3.3.3 Control Strategy:

The main aim of the control strategy implemented to control a D-STATCOM used for voltage mitigation is to control the amount of reactive power exchanged between the STATCOM and the supply bus. When the PCC voltage is less than the reference (rated) value then the D-ATACOM generates reactive power and when PCC voltage is more than the reference (rated) value then the D-ATACOM absorbs reactive power.

To achieve the desired characteristics, the firing pulses to PWM VSI are controlled. The actual bus voltage is compared with the reference value and the error is passed through a PI controller. The controller generates a signal which is given as an input to the PWM generator. The generator finally generates triggering pulses such that the voltage imbalance is corrected. The block diagram of the control circuit is shown in Fig. 3.8.

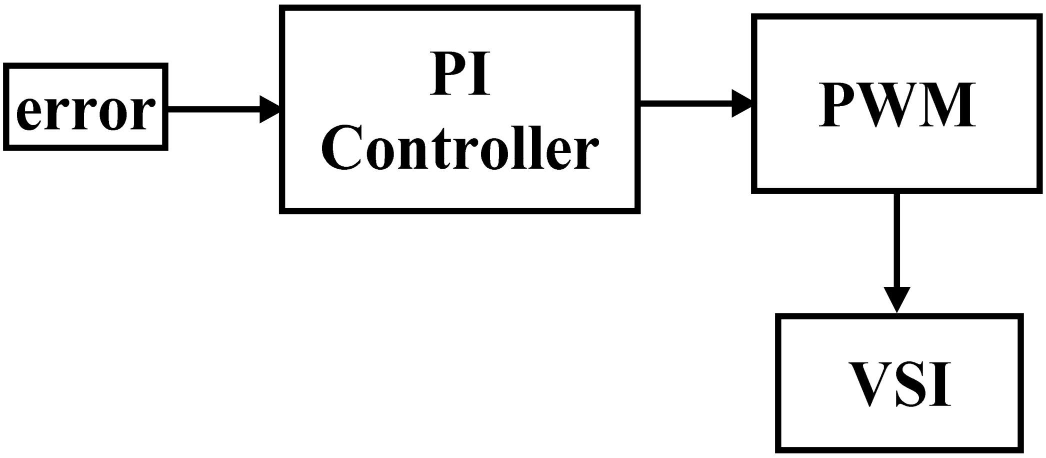


Fig.3.8 Block Diagram of the Control Circuit of D-STATCOM

3.3.4 Applications of D-STATCOM:

The applications of the D-STATCOM are-

- Stabilize the voltage of the power grid
- Reduce the harmonics
- Increase the transmission capacity
- Reactive power compensation
- Power Factor correction

3.4 Auto-Transformer

An auto transformer is a single winding transformer where there is no isolation between the primary and secondary windings. This device requires less conductor material in its construction and is of less size and weight when compared to the normal two winding transformer. This device can be used in mitigating the voltage sag when controlled properly. The principle of operation and the control technique are explained below.

3.4.1 Basic Structure:

The basic structure of an auto transformer is shown in Fig. 3.9. In this circuit configuration the secondary voltage is more than the primary voltage and the transformer operates as a step-up transformer. This configuration is used in voltage sag mitigation.

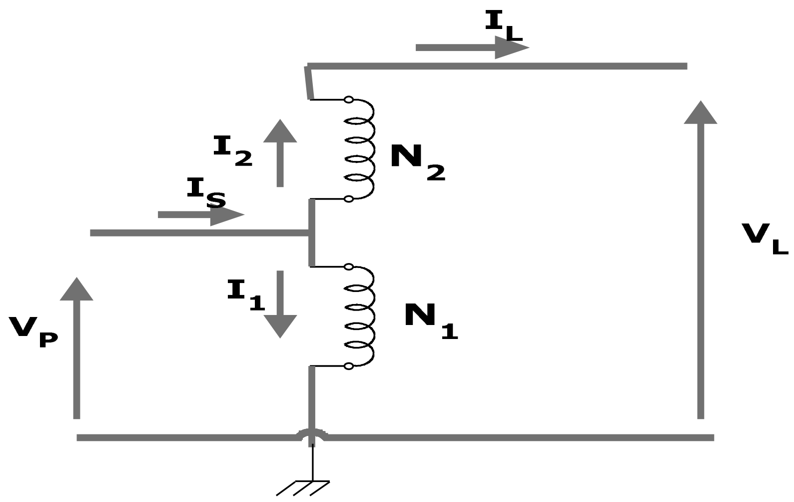


Fig.3.9 Circuit Diagram of an Auto-Transformer

From the circuit diagram,

V_P is the primary voltage

V_L is the load voltage

I_S is the source current

I_L is the load current

The turns ratio N_1:N_2 is taken as unity and the relation between primary and secondary voltages and currents is given by the equation (3.1).

$$\frac{V_L}{V_P} = \frac{I_S}{I_L} = \frac{N_1 + N_2}{N_1} \qquad (3.1)$$

3.4.2 Operating Principle:

The auto transformer is controlled by a PWM operated power electronic switch. The single-phase diagram of a power system network with a PWM switched auto transformer used for voltage sag mitigation is shown in Fig. 3.10.

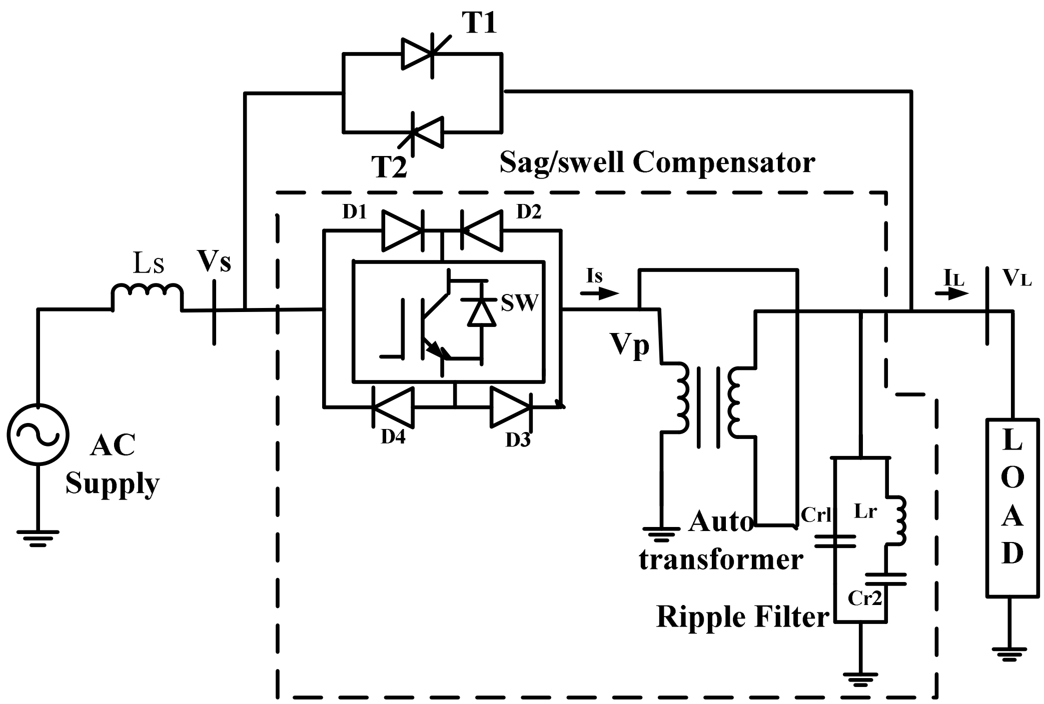


Fig.3.10 Voltage Sag Mitigation Scheme Using Auto Transformer

The circuit contains the following components-

- **An IGBT Switch:** This switch is operated based on the pulses generated by the PWM generator and controls the auto transformer operation.
- **Auto-Transformer:** It is used to boost the voltage so that the load voltage remains constant irrespective of the variations in the supply voltage. It is controlled by the IGBT switch.
- **Ripple Filter:** The output voltage given by the auto-transformer contains harmonics along with the fundamental component. Thus, these harmonics should be filtered out to maintain the THD for the given system voltage at the load should be within the IEEE standard norms. Therefore, a ripple filter is used at the output of the auto-transformer.
- **Bypass Switch:** There is a bypass switch made of SCR's connected in anti-parallel. This switch is used to bypass the auto-transformer during the normal operation. During voltage sag condition, this switch remains off and auto-transformer operates.

The single-phase circuit diagram during voltage sag condition is shown in Fig. 3.11. Here the bypass switch is off and the auto-transformer works based on the IGBT switch operation to generate required voltage on the load side [7].

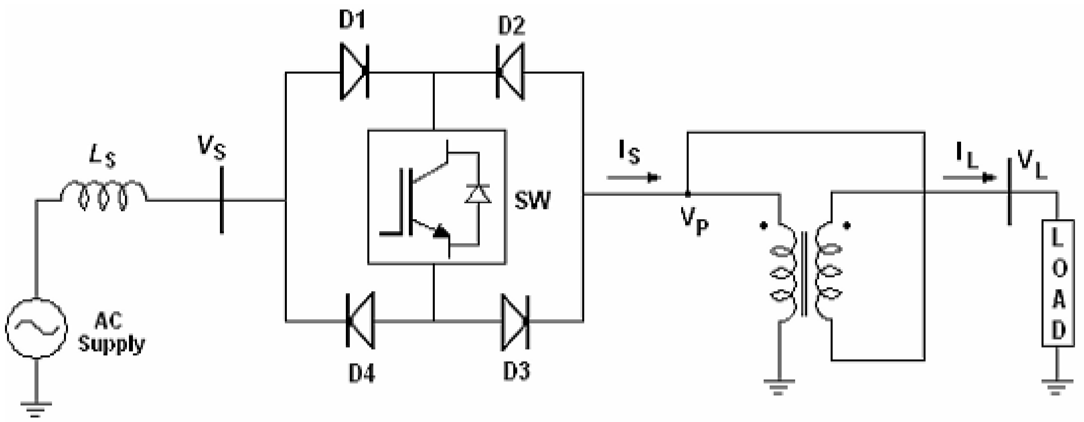


Fig.3.11 Single-phase Circuit Diagram during Voltage Sag

3.4.3 Control Strategy:

The main aim of the control strategy is to control the pulses generated to the IGBT switch such that the auto-transformer generates desired voltage to mitigate the voltage sag. The RMS value of the load voltage is compared with a reference value (V_{ref}). Under normal operating conditions there is no error and no pulses are generated to the IGBT switch and auto-transformer do not work. When there is voltage sag then an error occurs and based on the error value PWM generator generates pulses to the IGBT switch. Accordingly, the auto-transformer operates and the load voltage is maintained constant [7]. The block diagram of the control Strategy is shown in Fig. 3.12.

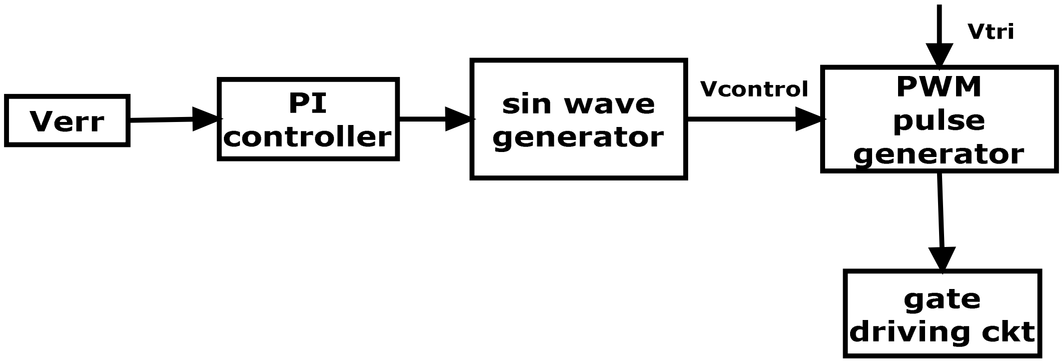


Fig.3.12 Block Diagram of Control Circuit

The voltage error is passed through a PI controller and it generates a phase angle δ. With this phase angle a control voltage is generated [7] using sine wave generator by using equation (3.2)

$$V_{control} = m_a \sin(\omega t + \delta) \quad (3.2)$$

Where m_a is the modulation index

The magnitude of the control voltage is dependent on the phase angle δ. The phase angle is proportional to the degree of disturbance [7]. Here the voltage which has been generated called control voltage is compared with the triangular voltage V_{tri} for the cause to generate the pulses which can be fed to the IGBT switch. In this way the auto transformer is controlled to mitigate the voltage sag.

3.4.4 Advantages:

The PWM switched auto-transformer is advantageous over the other devices in mitigating the voltage sag. The advantages are as follows-

- Less cost
- Less number of switches required
- Reduced gate driver circuit size
- No energy storage device

3.5 SUMMARY:

This chapter presents different devices used for mitigating the voltage sag. It presents the basic structure and operating principle of three main devices used for voltage sag mitigation- DVR, D-STATCOM, Auto-Transformer. It also presents the control techniques to control these devices.

CHAPTER 4

SIMULATION RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

There are many techniques to mitigate the voltage sag. Among them the best way is to use a device at the point of interest to regulate the voltage. The devices used for this purpose are already discussed along with their control techniques in the before chapter. These control strategies are simulated in MATLAB SIMULINK. This chapter presents the simulation results and makes a comparative study between these devices based on their performance.

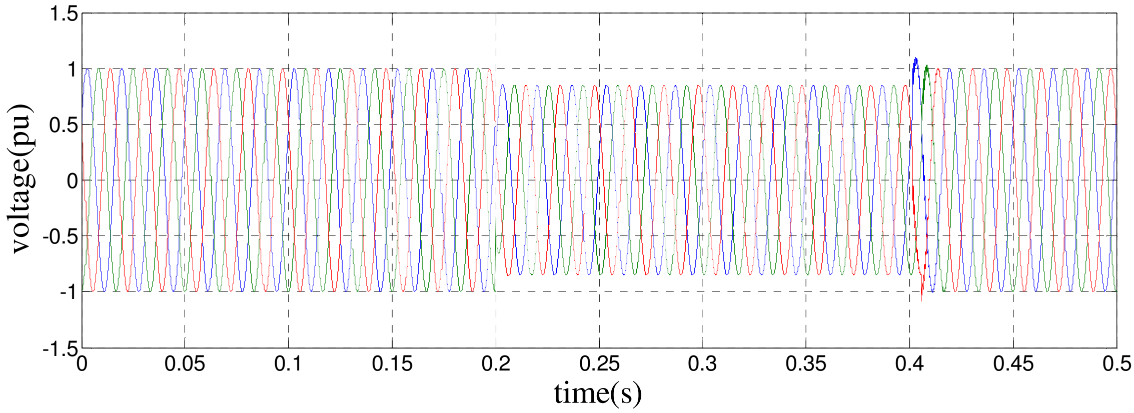
4.2 SIMULATION RESULTS USING DVR:

The system parameters used for simulation using DVR are given in Table-II. The line frequency is maintained at 60 Hz and the supply voltage is 415V.

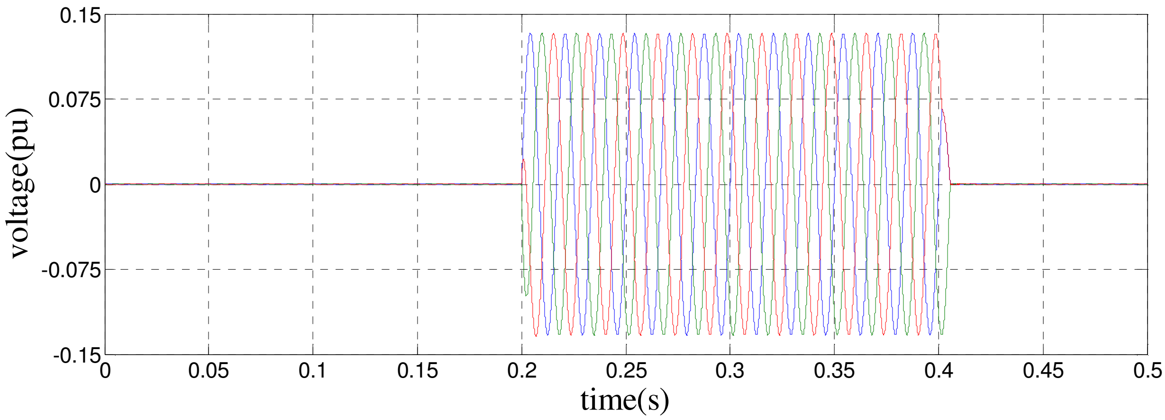
Table-II System parameters used for DVR simulation

Main Supply Voltage	415V
Line impedance	Ls =0.5mH Rs = 0.1 Ω
Series transformer turns ratio	1:1
DC Bus Voltage	100V
Filter Inductance	1mH
Filter Capacitance	1μF
Load Active Power	3KW
Load Inductance	60mH
Line Frequency	60Hz

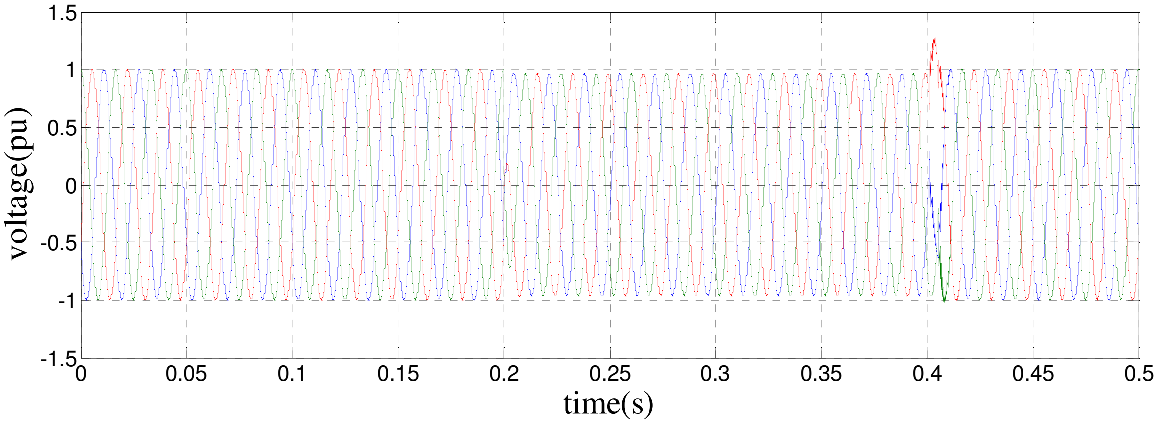
Voltage sag is initiated in the system by connecting an extra load for certain period of time. Here the extra load is connected to the system from 0.2s to 0.4s. Thus, during this time period the voltage at the load bus i.e., at the point of coupling (PCC) drops as shown in Fig. 4.1(a). Here the voltages are taken in per unit values and the voltage sag can be observed in Fig. 4.1(a) as the voltage decreases from its reference (rated) value of 1 p.u. To compensate this dip in voltage the DVR generates the compensation voltage as shown in Fig. 4.1(b). This voltage is in addition to the supply voltage. After compensation the load voltage is as shown in Fig. 4.1(c). DVR responds slowly to the change in voltage. Thus, there is some imbalance at the starting and ending point of the sag due to slight error that occur in adding the compensating voltage to the system voltage. This is clearly seen in Fig. 4.1(c). The THD of the load voltage is shown in Fig. 4.1(d).



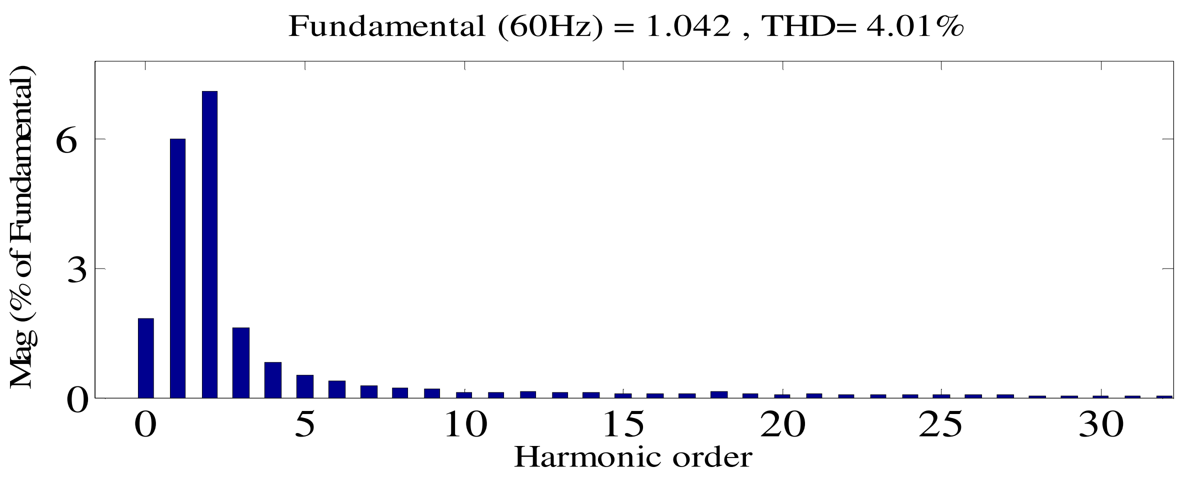
(a)



(b)



(c)



(d)

Fig.4.1 Simulation Results Using DVR (a) Voltage Sag (b) Voltage generated by DVR (c) Load Voltage after Compensation (d) THD of Load Voltage after Compensation

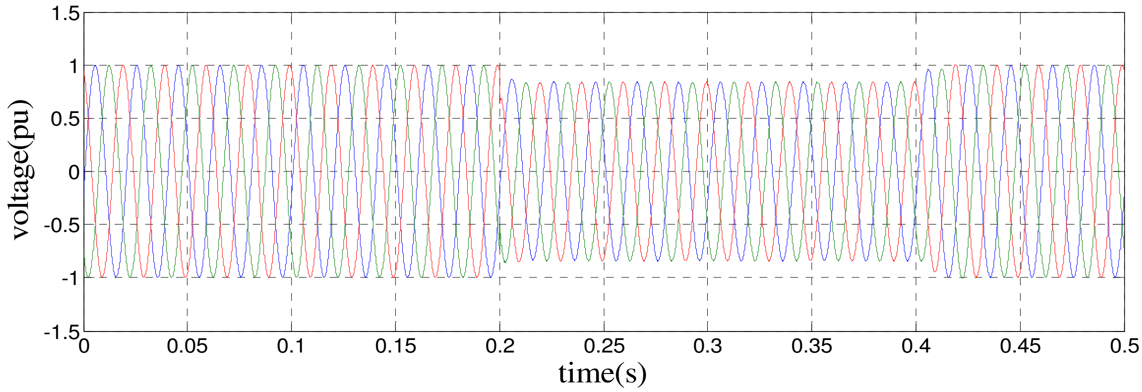
4.3 SIMULATION RESULTS USING D-STATCOM:

The system parameters used for simulation using D-STATCOM are given in Table-III.

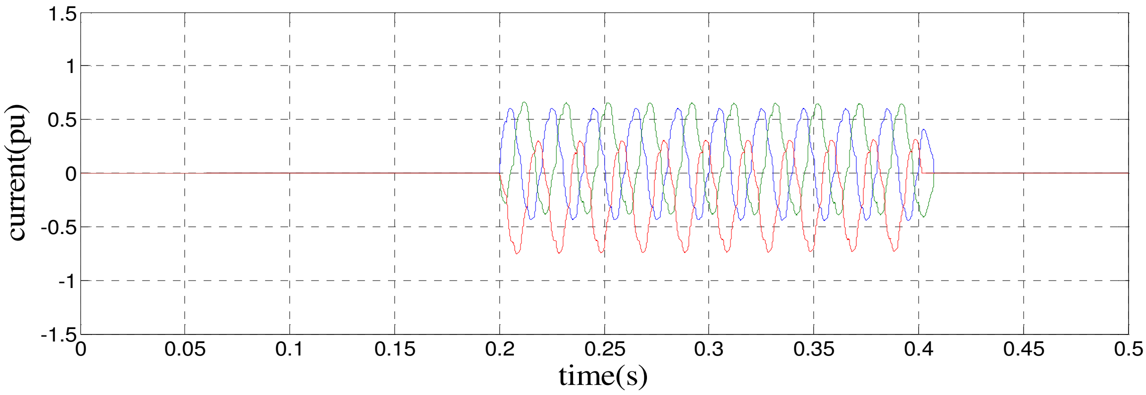
Table-III System parameters used for D-statcom simulation

Main Supply Voltage	415V
Coupling Transformer Voltage	200V
Coupling Transformer Turns Ratio	1:1
DC Bus Voltage	200V
Capacitance	750F
Load Active Power	20KW
Line Frequency	60HZ

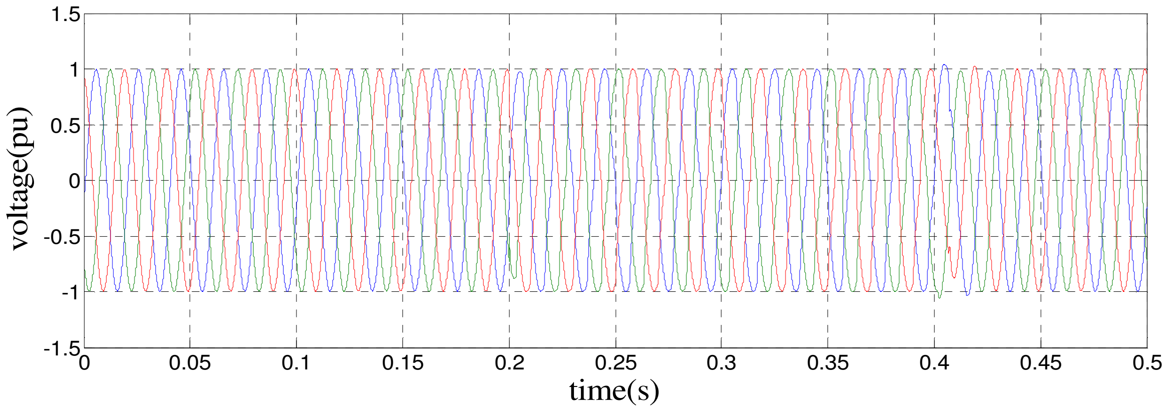
As in the case of DVR, voltage sag is created for simulation with D-STATCOM by connecting an extra load in the circuit. The resultant dip in the voltage at the PCC in per unit is shown in Fig. 4.2(a). Now the control circuit of the D-STATCOM gets activated. As it is a shunt connected device, it generates compensating current which is injected into the system. Based on the magnitude of this compensation current reactive power exchange takes place between the D-STATCOM and the transmission line. Based on this the load bus voltage is regulated. The waveform of the compensation current is shown in Fig. 4.2(b) and the waveform shows that the compensation current is not balanced. This affects the voltage at PCC and increases its harmonic content. The final voltage at the load bus after compensation is shown in Fig. 4.2(c). The THD of the load bus voltage is shown in Fig. 4.2(d). As said earlier, the THD is more due to the imbalanced nature of compensating current.



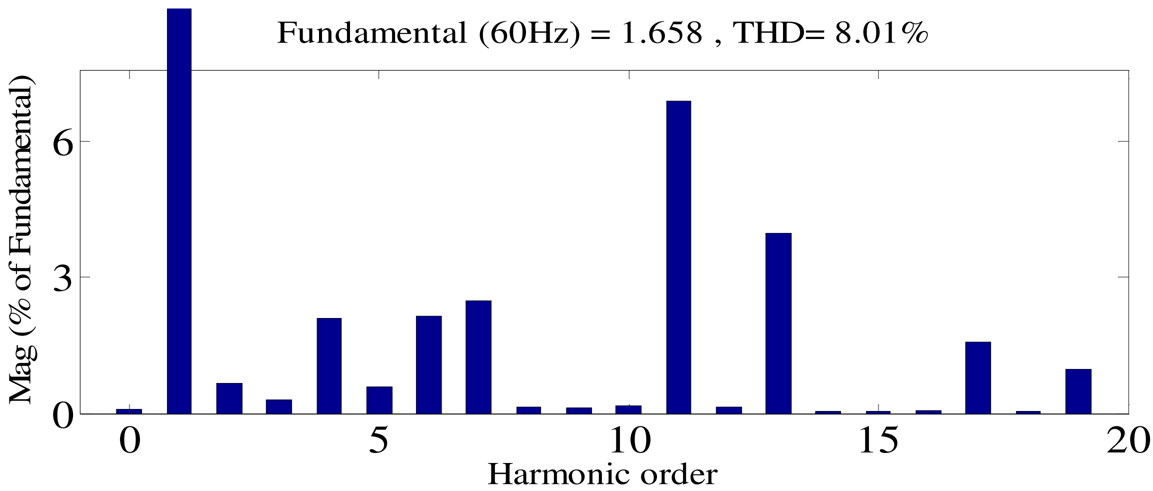
(a)



(b)



(c)



(d)

Fig.4.2 Simulation Results Using D-STATCOM (a) Voltage Sag (b) Compensation Current generated by D-STATCOM (c) Load Voltage after Compensation (d) THD of Load Voltage after Compensation

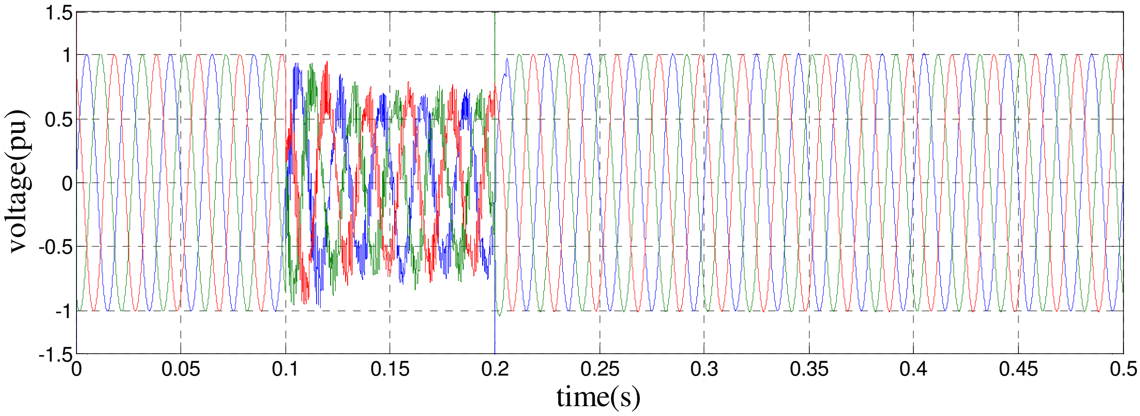
4.4 SIMULATION RESULTS USING PWM SWITCHED AUTO-TRANSFORMER:

The system parameters used for simulation with an auto-transformer are shown in Table-IV.

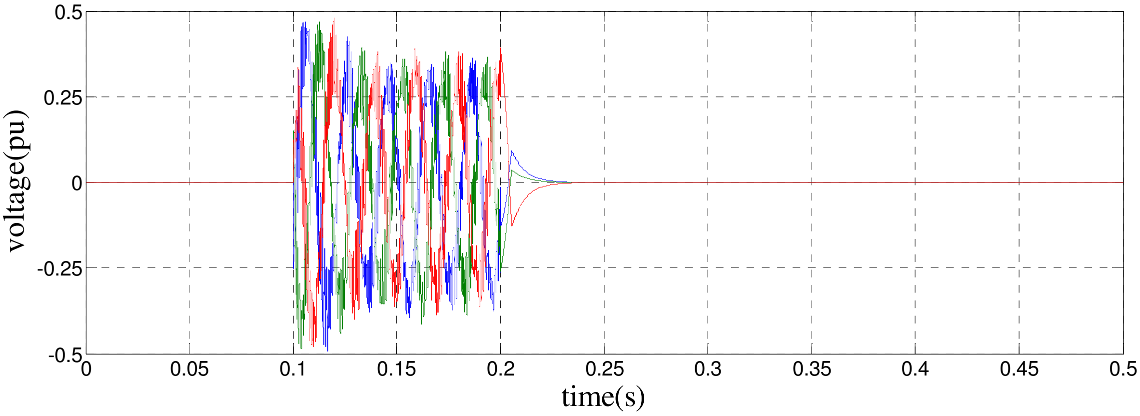
Table-IV System parameters used for Autotransformer simulation

Supply	3-Phase100 MVA, 11kV, 60 Hz , AC supply
Autotransformer	Primary: 6.35 kV, 100MVA, 60 Hz Secondary: 6.35KV ,100 MVA, 60 Hz
Ripple filter at output of Autotransformer	Lr = 200 mH Cr1 = Cr2 = 100μF
Load Active Power	10KW
Load Reactive Power	10KVAr

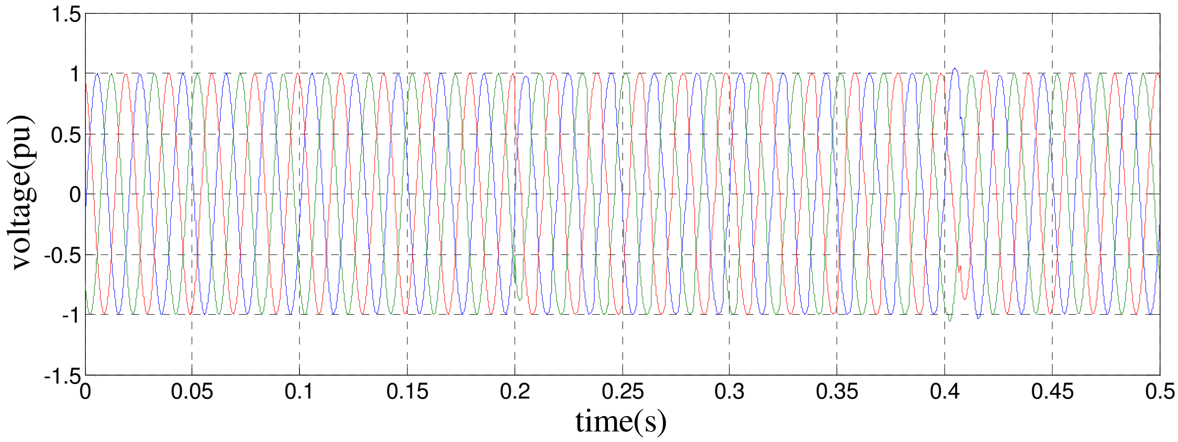
Voltage sag is created in the system from 0.1ms to 0.2ms and the auto transformer acts during this period to mitigate the voltage sag. The voltage at PCC when sag is created is shown in Fig. 4.3(a). The compensation voltage injected by the auto-transformer is shown in Fig. 4.3(b). The voltage at the load bus after compensation is shown in Fig. 4.3(c) and the THD of the load voltage is shown in Fig. 4.3(d). From the FFT analysis it clearly illustrates that the auto transformer is efficient in mitigating the voltage sag by reducing the load voltage harmonics to a great extent.



(a)



(b)



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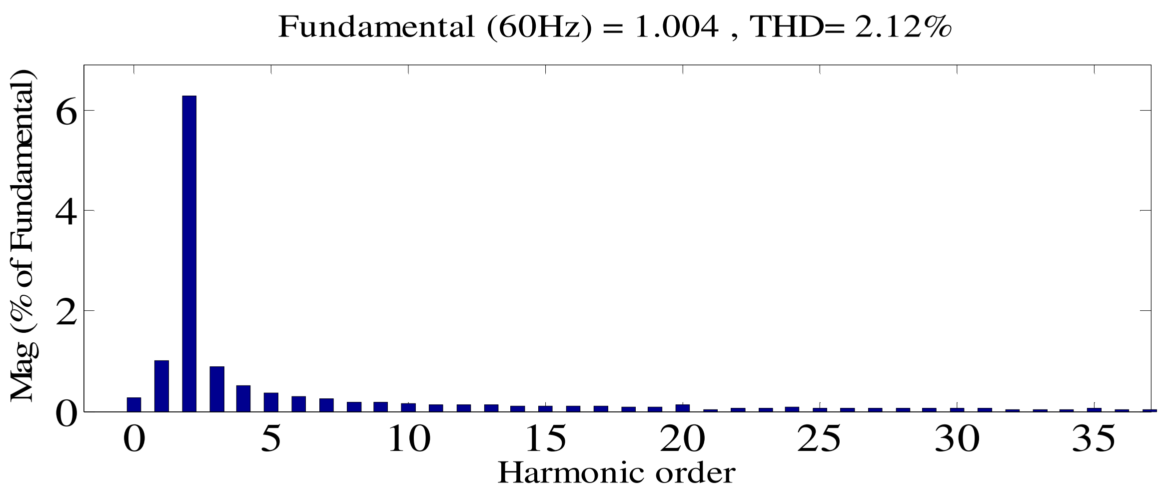

(d)

Fig.4.3 Simulation Results Using Auto-Transformer (a) Voltage Sag (b) Compensation Voltage generated by Auto-Transformer (c) Load Voltage after Compensation (d) THD of Load Voltage after Compensation

4.5 COMPARATIVE STUDY

A comparative study is made between three above discussed devices for mitigating voltage sag. The comparative study is based on the THD of the load voltage and is shown in Table-IV. From this study it is clear that the Auto-Transformer is more efficient in mitigating the voltage sag. And also the advantage of auto transformer is that the number of power electronic switches used is reduced. Hence the switching losses are reduced. Among DVR and D-STATCOM, DVR is better in terms of harmonic reduction. Though D-STATCOM acts faster than DVR, it introduces harmonics. And also D-STATCOM requires more apparent power injection than DVR for a given voltage sag .

Table-V Comparative Study

Device Name	THD of Load Voltage
DVR	4.01%
D-STATCOM	8.01%
Auto-Transformer	2.12%

4.6 SUMMARY:

This chapter presents the MATLAB SIMULINK simulation results of DVR, D-STATCOM and PWM switched Auto-Transformer. Each device performance in mitigating voltage sag is studied and analyzed. A comparative study is also made based on the THD of the load voltage after compensation. From the comparative study it can inferred that the PWM switched auto-transformer is efficient in mitigating the voltage sag.

CHAPTER 5

CONCLUSIONS

5.1 Conclusions

5.2 Future Scope

5.1 CONCLUSIONS:

The demand for electric power is increasing at an exponential rate and at the same time the quality of power delivered became the most prominent issue in the power sector. Thus, to maintain the quality of power the problems affecting the power quality should be treated efficiently. Among the different power quality problems, voltage sag is one of the major one affecting the performance of the end user appliances. In this project the methods to mitigate the voltage sag are presented. From this project, the following conclusions are made-

- Among the different methods to mitigate the voltage sag, the use of FACT devices is the best method
- The FACT devices like DVR, D-STATCOM are helpful in overcoming the voltage unbalance problems in power system
- DVR is a series connected device and injects voltage to compensate the voltage imbalance
- D-STATCOM is a shunt connected device and injects current into the system
- These devices are connected to the power network at the point of interest to protect the critical loads
- These devices also have other advantages like harmonic reduction, power factor correction
- The amount of apparent power infusion required by D-STATCOM is higher than that of DVR for a given voltage sag
- DVR acts slowly but is good in reducing the harmonic content
- Both DVR and D-STATCOM require more number of power electronic switches and storage devices for their operation
- To overcome this problem, PWM switched auto-transformer is used for mitigating the voltage sag
- Here the number of switches required are less and hence the switching losses are also reduced
- The size and cost of the device are less and hence PWM switched auto transformer is an efficient and economical solution for voltage sag mitigation

5.2 FUTURE SCOPE:

- Implementation of digital controllers to control the power electronic switches present in the device
- To study the operation of the devices in mitigating other voltage problems that occur in power system

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